

**UNCERTAINTY REQUIREMENTS IN RADIATIVE FORCING
OF CLIMATE CHANGE**

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Uncertainty Requirements in Radiative Forcing of Climate Change

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ABSTRACT

The continuing increase in atmospheric carbon dioxide makes it essential that climate sensitivity, the change in global mean temperature that would result from a given radiative forcing, be quantified with known uncertainty. Present estimates are quite uncertain, 3 ± 1.5 K for doubling of CO₂. Model studies examining climate response to forcing by greenhouse gases and aerosols exhibit large differences in sensitivities and imposed aerosol forcings that raise questions regarding claims of their having reproduced observed large scale changes in surface temperature over the twentieth century. Present uncertainty in forcing, due largely to uncertainty in forcing by aerosols, precludes meaningful model evaluation by comparison with observed global temperature change or empirical determination of climate sensitivity. Uncertainty in aerosol forcing must be reduced at least three-fold for uncertainty in climate sensitivity to be meaningfully reduced and bounded.

IMPLICATIONS

The present estimate of the global average climate sensitivity, 3 ± 1.5 K for doubling of CO₂, is too uncertain to usefully inform policymaking regarding mitigation of greenhouse warming or adaptation to a warmer future climate. Approaches to determining this sensitivity, either through use of climate models or by empirical inference, are limited at present by uncertainty in radiative forcing of climate change over the industrial period, which is dominated by uncertainty in forcing by aerosols. For uncertainty in climate sensitivity to be meaningfully reduced and bounded, the present uncertainty in aerosol radiative forcing must be reduced at least three-fold, to less than 0.5 W m^{-2} .

INTRODUCTION

The sensitivity of global mean temperature change to an increase in atmospheric CO₂ is not well established. The complexity of the climate system precludes calculation of the response of Earth's climate to a change in a radiative flux component (forcing) from well established physical laws. Consequently determination of global climate sensitivity is a subject of intense research. This work is reviewed from time to time by pertinent national and international bodies. One such landmark review was that of a 1979 National Research Council panel chaired by Charney¹, which concluded: “We estimate the most probable global warming for a doubling of CO₂ to be near 3 degrees C, with a probable error of plus or minus 1.5 degrees.” More recently the Intergovernmental Panel on Climate Change (IPCC)^{2,3} concluded that “Climate sensitivity [to CO₂ doubling] is likely to be in the range 1.5 to 4.5°C.” These estimates must be considered somewhat subjective. They are based mainly on calculations with climate models constrained, especially for the IPCC estimate, by observation of the extent of warming over the industrial period and concurrence of modeled and observed warming. Neither the Charney panel nor the IPCC quantitatively specified the meaning of their uncertainty bounds (e.g., 2σ), but in the case of the Charney estimate, an NRC panel⁴ three years later expressed its understanding that “the Charney group meant to imply a 50% probability that the true value would lie within the stated range.” Remarkably, despite some two decades of intervening work, neither the central value nor the uncertainty range has changed.

The large uncertainty range, a factor of 3, in present estimates of climate sensitivity renders such estimates not particularly useful from the perspective of developing policy regarding either reduction of greenhouse gas emissions or adaptation to a new, increasingly warm climate. While some comfort might be taken in a sensitivity at the low end of the range $\Delta T_{2\times} = 1.5$ K (where, $\Delta T_{2\times}$ is the change of mean surface temperature that would result from a doubling of atmospheric CO₂; see Box), a sensitivity at the high end of the range would, for a doubled-CO₂ atmosphere, which is expected to occur well within this century, result in an overwhelming change in Earth's climate. In this context one must note that the increase in global mean temperature from the middle of the last ice age to the present interglacial is estimated as 5 or 6 K.

These considerations speak to the need to decrease the uncertainty associated with the climate sensitivity. There are two independent approaches to doing this, by using climate models and by empirical inference from the change in temperature over the industrial period. Both approaches require knowledge of radiative forcing of Earth's climate over the industrial period.

In addition to radiative forcing by increased CO₂, human activities have resulted in other radiative influences on climate which are of comparable magnitude and which have occurred over roughly the same time period. These include forcing by increased atmospheric mixing ratios of other long-lived greenhouse gases (GHGs) principally methane, nitrous oxide, chlorofluorocarbons, and tropospheric ozone, and a decrease in greenhouse forcing by stratospheric ozone. The other major forcing is due to anthropogenic aerosols. Atmospheric aerosol particles scatter and absorb shortwave (solar) radiation (direct effects) and modify the reflective properties and persistence of clouds (indirect effects)⁵. Principal aerosol forcing components are sulfates (cooling), organic carbon (cooling) and black carbon (warming), all due largely to emissions associated with fossil fuel combustion, and organics from biomass combustion (cooling). Mineral dust from disturbed soils both scatters shortwave radiation (cooling) and absorbs it (warming, if over brighter surfaces). The forcings by these aerosol components are estimated based on loadings calculated by chemical transport models (so-called “forward” calculations⁶) evaluated by comparison with observation. There are likely to have been other, relatively minor, secular changes in radiative flux components due to aviation induced contrails and cirrus, changes in surface reflectivity due to land use changes, and changes in solar luminosity. These influences are summarized in Figure 1, which shows the estimates by the IPCC working group on radiative forcing⁷ of these radiative forcings over the industrial period and of the associated uncertainties.

The thesis of this article is that these uncertainties in forcing are too great to be useful for inferring climate sensitivity empirically from observed change in global mean temperature over the industrial period or for evaluating performance of climate models over this period.

RADIATIVE FORCING OF CLIMATE CHANGE

The radiative forcing concept is rooted in studies with general circulation models that have examined climate change in response to different kinds of radiative forcing. A consistent finding of such studies is that the change in global mean temperature per forcing, that is the climate sensitivity, is, to a good approximation, independent of the nature of the forcing, for example forcing due to changes in CO₂ mixing ratios, mixing ratios of other GHGs⁸, aerosol direct forcing⁹, or the solar constant¹⁰, and independent as well of the geographical distribution of the forcing⁹. These model-based studies are the basis of the climate sensitivity hypothesis.

An immediate consequence of the forcing-response paradigm is that forcings are additive. This hypothesis provides a path forward to calculating radiative forcing over the industrial period

by adding the forcings, as shown in the bars at the right of Figure 1. The first bar gives the algebraic sum of the several aerosol forcings indicated by bars in the IPCC figure. The resulting forcing, -0.46 W m^{-2} is small compared to the forcing due to the well mixed GHGs, 2.42 W m^{-2} , suggesting slight aerosol influence over the industrial period. However a problem arises in estimating this forcing because the IPCC working group declined to give a best estimate for forcing by mineral dust and for aerosol indirect forcing. The absence of a number implicitly sets its estimate to zero. In the case of the dust, the uncertainty range is roughly symmetric about zero, so taking the best estimate of this forcing as zero does not greatly affect the value of the total aerosol forcing. However for the indirect aerosol forcing, zero is at one end of a large uncertainty range, so setting this (negative) forcing to zero has the effect of biasing the total to far too great a positive value.

The IPCC working group on radiative forcing⁷ estimated the range of the aerosol indirect forcing over the industrial period between 0 and -2 W m^{-2} . Table 6.6 of the radiative forcing chapter of the IPCC report lists some 17 independent estimates ranging from -0.3 to -1.85 W m^{-2} , and other, even greater (negative) estimates have been published; the working group extended the range upward to 0 to account for possible absorption by black particles in clouds. In any event, for the purpose of estimating total aerosol forcing over the industrial period it seems certain that zero leads to a biased estimate. Using the mid-points of the uncertainty ranges for both the mineral dust forcing and the aerosol indirect forcing results in the total aerosol forcing (second bar at the right of Figure 1) being -1.56 W m^{-2} , almost two-thirds of the forcing by long lived GHGs. Also shown are estimates of the total radiative forcing calculated in the same way, with mineral dust and aerosol indirect forcings taken as zero (bar 3) and as the mid-points of the uncertainty ranges (bar 4). The latter estimate, 1.21 W m^{-2} , is roughly half the total forcing obtained if these two forcings are taken as zero. It should be evident that in any empirical inference of climate sensitivity or in any evaluation of performance of climate models over the industrial period the result will be quite sensitive to the choice of aerosol forcing.

Also shown for each estimate of total aerosol forcing and total forcing are two estimates of the associated uncertainty. For the left I-beam of each pair the upper and lower limits are calculated as the algebraic sums of the upper and lower limits, respectively, of the uncertainties associated with each of the individual forcings. For the right I-beam the limits are calculated as the square root of the sums of the squares of the differences between the limits of the respective uncertainty ranges and the estimated forcings (RSS method). The algebraic sum would be appropriate for positively correlated forcings, as would be the case for direct and indirect aerosol forcing, whereas the RSS method would be appropriate for uncorrelated forcings. An alternative

means of propagating these uncertainties was presented by Boucher and Haywood,¹¹ who used a Monte Carlo approach for several assumed shapes of the probability distribution functions (PDFs) of the uncertainties to obtain PDFs of the overall uncertainty range. The peaks of the PDFs for the total forcing were at about 1 W m^{-2} , with the bulk of the PDFs between 0 and 2 W m^{-2} and with some probability (3 to 25 %, depending on assumption in propagating the uncertainty) that the total forcing is negative. By any reckoning the uncertainty in the total radiative forcing of climate change over the industrial period is quite large relative to the forcing by greenhouse gases.

It is useful to examine the reasons for the large uncertainties associated with the several forcings. Here the comparison between the well mixed GHGs and tropospheric ozone is instructive. The relative uncertainty for GHGs is much less than that for tropospheric ozone yet the absolute uncertainties are comparable. The present and preindustrial atmospheric mixing ratios of the well mixed GHGs are well established, from contemporary measurements at a relatively small number of locations and preindustrial measurements from ice cores, and the uncertainty in forcing is thus due largely to issues of radiation transfer, as exemplified by differing estimates of forcing by CO_2 (see Box). For tropospheric ozone the uncertainty in forcing is dominated by uncertainty in the increase in mixing ratio of this relatively short lived and heterogeneously distributed atmospheric species above its preindustrial value. Similar considerations apply to the aerosol forcing. The large relative uncertainty in the direct forcing by sulfate is due mainly to issues of atmospheric chemistry – how much is formed, how long the material resides in the atmosphere – and aerosol microphysics – the size distribution and its response to relative humidity¹². Relatively little uncertainty is due to uncertainty in the treatment of the radiative effects of this aerosol, provided the loading and size distribution are specified¹³. Climate forcing is quite sensitive to incremental aerosol loading. An increase in aerosol scattering optical depth of 0.03 in cloud-free areas of the planet, an amount close to the limit of detection of well calibrated instruments^{14,15}, less than the natural aerosol optical depth in pristine regions of the southern hemisphere¹⁴, and well less than day to day fluctuations in rural, mid-continental North America¹⁵, gives rise^{5, 13} to a radiative forcing of about -1 W m^{-2} . The indirect aerosol effect, which is due to an increase in multiple scattering in and reflectivity of clouds of intermediate optical depth due to the presence of enhanced concentrations of aerosol particles that serve as nuclei for cloud drop formation¹⁶, is quite sensitive to cloud drop number concentration; an increase in 30% of the number concentration of cloud droplets in marine stratus clouds is estimated⁵ to yield a global average radiative forcing of about -1 W m^{-2} . The uncertainty

in total aerosol forcing ($+1.25 \text{ W m}^{-2}$; -1.45 W m^{-2} by the RSS method) dominates the uncertainty in total forcing.

APPROACHES TO DETERMINING CLIMATE SENSITIVITY

As noted above two independent approaches might be taken to determining sensitivity of global mean temperature to a radiative forcing, studies with climate models and empirical inference. In principle if climate models were accurate and complete they might be used with confidence to predict the response of future climate to future forcing. In practice these models embody numerous assumptions, parameterizations, and approximations of the variables and phenomena being represented – water vapor, clouds, precipitation, snow and ice, radiation, transport of heat and water on all scales – the list goes on. The resolution of models is limited, typically at present to about 300 km, with the necessity to parameterize phenomena occurring at smaller scales. Much model evaluation is carried out by examination of their ability to model the present climate¹⁷. However even models which reproduce many aspects of the present climate rather well can still exhibit widely differing climate sensitivities. The IPCC 2001 survey¹⁸ of 15 current atmospheric GCMs that are coupled to mixed-layer upper ocean models reported a range of sensitivities to doubled CO_2 , $\Delta T_{2\times}$, of 2.0 to 5.1 K; average 3.5 K; standard deviation 0.92 K. Modeled climate sensitivity is highly dependent on parameterizations; for example a change in cloud parameterization in the UK Meteorological Office model changed modeled climate sensitivity to doubled CO_2 by a factor of 2.8, from 1.9 to 5.4 K¹⁹. The wide range in modeled climate sensitivities and the sensitivity to parameterization suggest that confidence in the ability of climate models to predict climate change in response to future forcings cannot be based on their ability to simulate present climate but rather must be gained from their ability to reproduce climate change over the industrial period.

Recent studies using coupled atmosphere-ocean models have included aerosol forcing in an effort to simulate transient climate response over the industrial period, some results of which are shown in Figures 2 and 3 and summarized in Table 1. In such studies it is necessary to assume a time profile (and spatial distribution) of the forcings to be represented in the model. The model is then run subject to these time dependent forcings and compared to a base case for which no forcing is applied. Because of internal variability within such models it is necessary to carry out some averaging. For studies with constant forcing differences this variability can be accounted for by running the model for sufficient time to obtain a stable average, but this cannot be done for runs with transient forcings, so internal variability is estimated by running ensembles of several transient calculations. Model performance is evaluated by comparison with the temperature

record observed over the industrial period. With inclusion of aerosol forcing each of the models fairly accurately reproduces this record; the modeled temperature increase over the period 1900-1990, for example (Table 1), is similar to the observed²⁰ increase over this period, $0.48 \text{ K} \pm 0.17 \text{ K}$ (2σ). Without exception the investigators assert that inclusion of aerosol forcing improves the comparison of their model simulations to the observed temperature trend. However it would seem that confidence in such agreement, and in turn in the correspondence between the temperature sensitivity employed in any given model and the actual sensitivity of Earth's climate system, must be tempered by the uncertainty in total forcing at present (and a fortiori as a function of time over the industrial period) and by the differing sensitivities of the several models (by up to a factor of 1.7) and aerosol forcings (by up to a factor of 1.8) employed in these studies. The inter-model spread in modeled temperature trend over the period 1900-1990 expressed as a fractional standard deviation is well less than the corresponding spread in either sensitivity or aerosol forcing (Table 1). Considerations such as these would seem to call into question confidence that can be placed in statements such as the following from the IPCC 2001 assessment of climate change²¹:

- “Simulations that include estimates of natural and anthropogenic forcing reproduce the observed large-scale changes in surface temperature over the 20th century.”
- “Most model estimates that take into account both greenhouse gases and sulphate aerosols are consistent with observations over this period.”
- “The large-scale consistency between models and observations can be used to provide an independent check on projected warming rates over the next few decades under a given emissions scenario.”
- “Detection and attribution studies comparing model simulated changes with the observed record can now take into account uncertainty in the magnitude of modelled response to external forcing, in particular that due to uncertainty in climate sensitivity.”

Certainly a major contributor, if not the major contributor, to the inability of such comparisons to narrow down the range of model sensitivity is the uncertainty in radiative forcing over the industrial period.

The alternative approach to determining model sensitivity is empirical. In essence, climate sensitivity would be evaluated as $\lambda = \Delta T / F$, where ΔT is the observed global-average temperature change over some period of record and F is the forcing over that period. The period of record might be the period from 1860 to the present, for which fairly reliable instrumental records are available, or might be some shorter period that is sufficiently long to allow coupling of

the atmosphere to the ocean mixed layer (about two years) and to average over short term variability due to El Niño cycles and the like (at least a decade). Inherent concerns with this approach deal with the transient nature of the response – that is, an argument that the full warming of the imposed forcing might not be realized during a given period of record. Alternative variants of this method would account for heat loss from the mixed layer to intermediate depths as measured in ocean surveys²². However this variant approach also is limited by considerations of uncertainty, again mainly uncertainty in forcing. For example Gregory et al.²³ found that the uncertainty in forcing was consonant with arbitrarily large sensitivity as (negative) aerosol forcing was increased such that the total forcing approached zero.

ESTIMATING THE REQUISITE UNCERTAINTY IN AEROSOL FORCING

For climate sensitivity to be evaluated empirically the fractional uncertainty in λ can be estimated to first order as

$$\frac{\delta\lambda}{\lambda} = \sqrt{\left(\frac{\delta\Delta T}{\Delta T}\right)^2 + \left(\frac{\delta F}{F}\right)^2}$$

where δF and $\delta\Delta T$ denote the uncertainties in F and ΔT respectively. A reasonable initial target uncertainty might be $\delta\lambda / \lambda = 30\%$ for example $\Delta T_{2\times\text{CO}_2} = (3 \pm 1) \text{ K}$. Setting such a target allows specification of required uncertainties in temperature anomaly and forcing. For example the required uncertainty in λ might be met for $\delta\Delta T / \Delta T \approx \delta F / F \approx 20\%$. An uncertainty of such magnitude is arguably already at hand for the temperature difference over the instrumental period (1861 to 2000), for which Folland et al.²⁴ estimate a fractional uncertainty (2σ) of 26%.

The requirement of a specific uncertainty in total forcing over such a period, e.g., 20%, allows the required uncertainty in aerosol forcing to be estimated. Here consideration is restricted just to forcing by GHGs F_g and aerosols F_a , setting aside other contributions to forcing and uncertainty. For this estimate total greenhouse gas forcing (well mixed gases plus stratospheric and tropospheric O_3) is taken equal to 2.6 W m^{-2} with an uncertainty of $\pm 10\%$ as given by the IPCC (Figure 1). The total forcing is the algebraic sum $F = F_g + F_a$, but as aerosol forcing is negative the relative uncertainty in the total forcing will be greater than that in either term, and if the two terms are comparable in magnitude, much greater. The requirement that uncertainty in aerosol plus greenhouse gas forcing not exceed 20% permits specification of an upper bound on the uncertainty in aerosol forcing; this requisite uncertainty is shown in Figure 4 as a function of (negative) aerosol forcing. No matter what the magnitude of the aerosol forcing, the requirement that the uncertainty in total forcing not exceed 20% means that the uncertainty in aerosol forcing

cannot exceed about 0.45 W m^{-2} ; the requirement on the aerosol uncertainty becomes increasingly stringent as the magnitude of (negative) aerosol forcing increases. This requirement may be compared to the present situation as summarized in Figure 1. For aerosol forcing about -1.2 W m^{-2} , which is still less than half that of GHG forcing, the requisite fractional uncertainty becomes the same as that currently ascribed to GHG forcing, i.e., about 10%, or 0.1 W m^{-2} . Essentially the same uncertainty in aerosol forcing would be required, as a function of secular time, as input to GCM calculations of the temperature anomaly trend over the industrial period.

Reducing the uncertainty in aerosol forcing to such an extent would represent an enormous challenge to the atmospheric research community. Nonetheless the need for reducing the present uncertainty by at least a factor of 3 and perhaps a factor of 10 or more seems inescapable if the uncertainty in climate sensitivity is to be reduced to an extent where it becomes useful for formulating policy to deal with global change. If this challenge is not met, it is likely that in another twenty years it will still not be possible to specify the climate sensitivity with uncertainty range appreciably narrower than it is at present.

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Table 1. Performance of climate models that include aerosol forcing in transient simulations

Model	Year	Sensitivity ^a $\Delta T_{2\times}$ K	1990 Aerosol forcing W m ⁻²	Modeled ΔT^b , GHG + aerosol K	Investigator characterization of model performance including aerosol forcing
UK Met Office ²⁵	1995	2.5	-0.6	0.48	Inclusion of sulphate aerosol forcing improves the simulation of global mean temperature over the last few decades.
Canadian Climate Model ²⁶	2000	3.5	-1.0	0.56	Observed global mean temperature changes and those simulated for GHG + aerosol forcing show reasonable agreement.
GFDL ²⁷	2000	3.4	-0.62	0.46	The surface temperature time series from the five GHG-plus-sulfate integrations show an increase over the last century, which is broadly consistent with the observations.
UK Met Office ^{29,30}	2000	3.35	-1.1	0.38 ^c	The ALL ensemble captures the main features of global mean temperature changes observed since 1860.
NCAR ²⁸	2003	2.18	-0.6	0.50	The time series from GHG + sulfates + solar shows reasonable agreement with the observations.
Range		1.32	0.5	0.18 0.10 ^d	
Fractional standard deviation, %		20	31	14 9 ^d	

^aAs stated by the investigators.^bModeled change in global mean temperature between 1900 and 1990 for greenhouse gas and aerosol forcing.^cTotal anthropogenic forcing; also includes stratospheric ozone forcing -0.4 W m⁻².^dOmitting UKMO 2000, which also included stratospheric ozone forcing.

Unit of measure for climate sensitivity. Any examination of uncertainty in climate sensitivity must consider the unit of measure. Traditionally the sensitivity of climate change has been expressed as a quasi-equilibrium change in global mean temperature that would result from a doubling of atmospheric mixing ratio of CO₂, $\Delta T_{2\times}$. The temperature sensitivity, a change in temperature due to a change in a radiative flux component has dimension temperature/(power per area), for which the systematic unit is K/(W m⁻²), and in this unit is commonly denoted by the symbol λ . Such a systematic unit for sensitivity is to be preferred because it is insensitive to uncertainty in the forcing due to doubling of CO₂. The conversion is given by $\lambda = \Delta T_{2\times} / F_{2\times}$, where $F_{2\times}$ is the forcing of doubled CO₂ relative to the unperturbed state, about 4 W m⁻². The use of $\Delta T_{2\times}$ as a unit of climate sensitivity implies that $F_{2\times}$ is known with small uncertainty and independent of the CO₂ mixing ratio of the unperturbed state; more importantly, comparison of sensitivities of different models assumes that all investigators obtain the same forcing for such a doubling.

The forcing associated with doubling of CO₂, $F_{2\times}$, was examined in an intercomparison of 15 atmospheric general circulation models reported by Cess *et al.* (31). In that study the base case was specified as 330 ppm and the perturbed case taken as 660 ppm, eliminating any contribution to variation that might have resulted from other choices. Likewise that intercomparison specified that the forcing was to be calculated as a net flux difference at a pressure altitude of 200 hPa, again potentially reducing the variation in the stated forcing associated with doubling of CO₂. Nonetheless the variation among the several models was substantial, with range 34% and fractional standard deviation 10.2%. Cess *et al.* noted that if the 15 models all exhibited equal climate sensitivity $\lambda = 1$ K/(W m⁻²), this variation in forcing per CO₂ doubling would lead to change in equilibrium temperature for doubled CO₂ ranging from 3.4 to 4.7 K and pointed out that this range is nearly half the often quoted range of uncertainty in $\Delta T_{2\times}$ of 1.5 to 4.5 K. The uncertainty associated with the use of $\Delta T_{2\times}$ as a measure of climate sensitivity is both substantial and wholly unnecessary. Nonetheless because of the widespread prior use of $\Delta T_{2\times}$ as a measure of sensitivity, it seems useful to retain this measure provided it is viewed as subsidiary and is uniquely and unambiguously related to the sensitivity in systematic units λ .

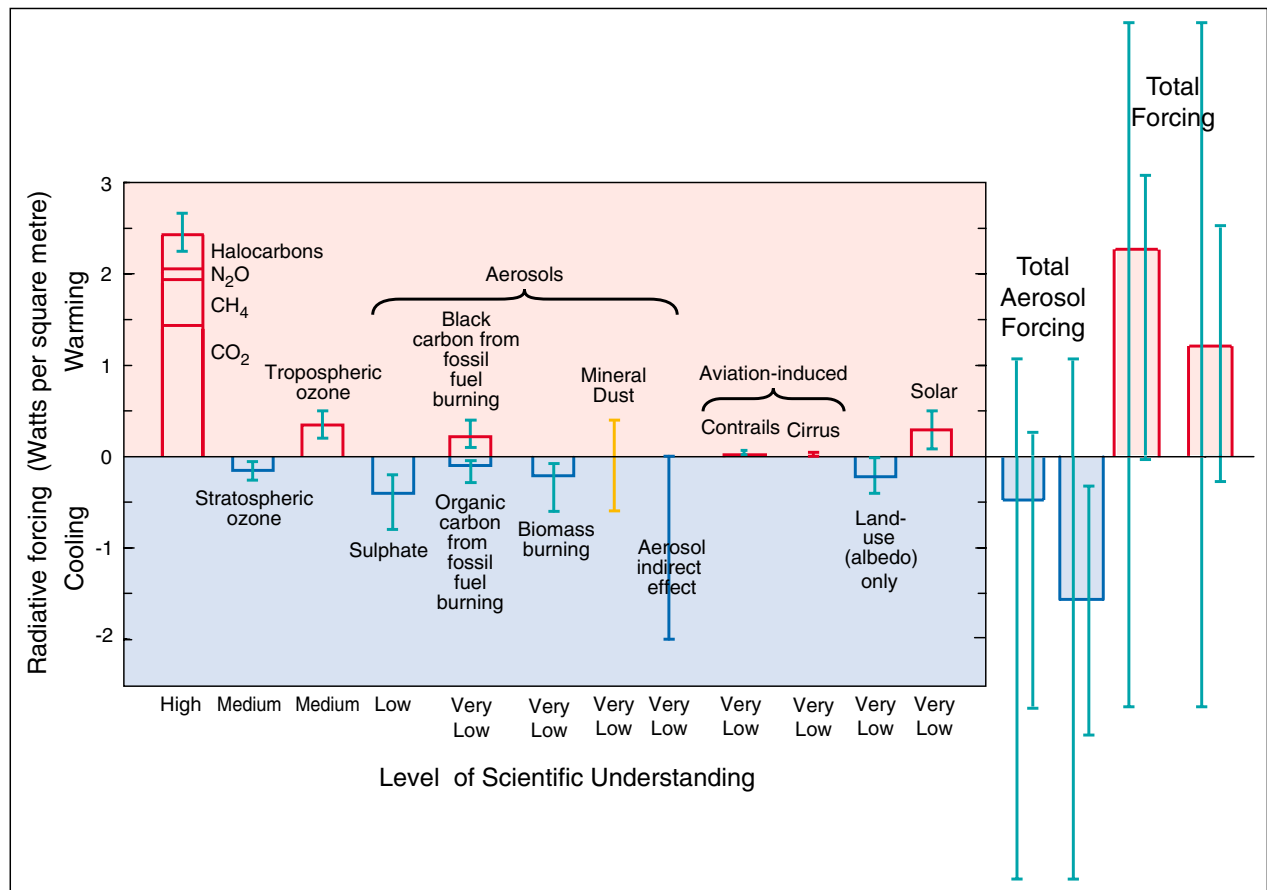


Figure 1. Global mean radiative forcing of climate change for the year 2000 relative to 1750 as given by the Intergovernmental Panel on Climate Change⁷ shown in the left portion of the figure. Positive bars denote warming forcings; negative bars denote cooling forcings; I-beams denote estimated uncertainties. For mineral dust and the aerosol indirect effect no estimates of the forcing were given, only uncertainty ranges. Level of scientific understanding represents the subjective judgment of the IPCC working group on radiative forcing of the reliability of the forcing estimate. Bars and I-beams at right denote estimates of total aerosol forcing, total forcing, and associated uncertainties. First bar denotes total aerosol forcing evaluated as algebraic sum of IPCC aerosol forcings, with mineral dust and aerosol indirect forcings taken as zero; for second bar these forcings are taken as the mid-points of the IPCC uncertainty ranges. Third and fourth bars denote total forcing evaluated in the same way, again with mineral dust and aerosol indirect forcings taken as zero and as the mid-points of the IPCC uncertainty ranges, respectively. For each bar two uncertainty estimates are provided. Upper and lower limits of the first (larger) uncertainty range are calculated as algebraic sum of upper and lower limits, respectively, of the uncertainties of the several forcings. Upper and lower limits of the second (smaller) uncertainty range are calculated as square root of the sum of the squares, respectively, of the of the upper and lower uncertainty ranges relative to the estimated forcings denoted by the bars.

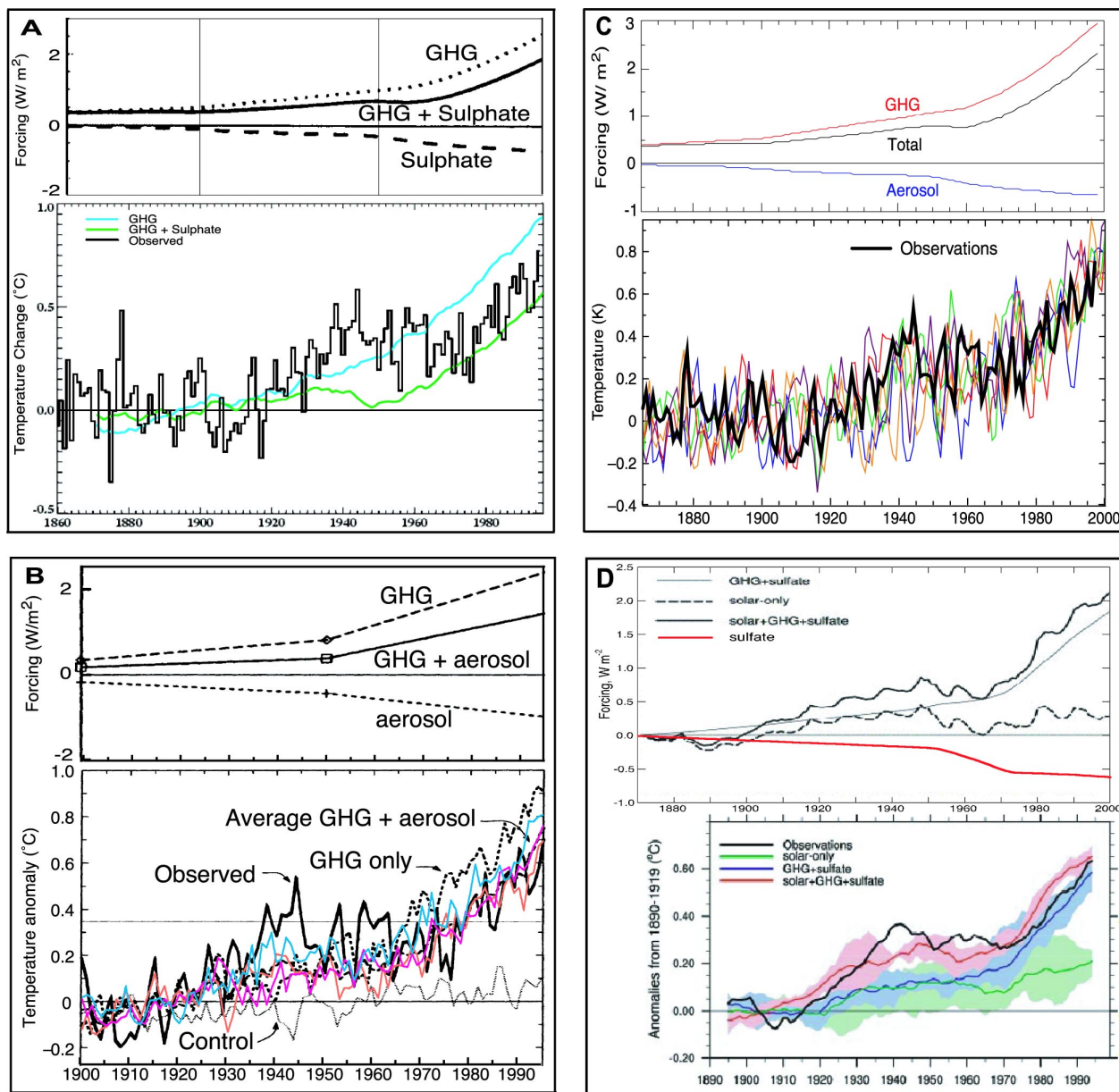


Figure 2. Global mean forcing and temperature anomaly in four climate models over the past 100 to 140 years. A, UK Meteorological Office model, 1995²⁵. B, Canadian Climate Model, 2000²⁶. C, Geophysical Fluid Dynamics Laboratory model, 2000²⁷. D, National Center for Atmospheric Research model, 2000²⁸. Multiple traces for forcings denote different combinations of imposed forcings. Multiple traces for temperature change in B and C and envelopes in D denote results from ensembles of multiple model runs with identical forcings and similar but slightly different initial conditions. Observed temperature anomaly, bold black. For model sensitivities, aerosol forcings, and investigator characterization of model performance see Table 1.

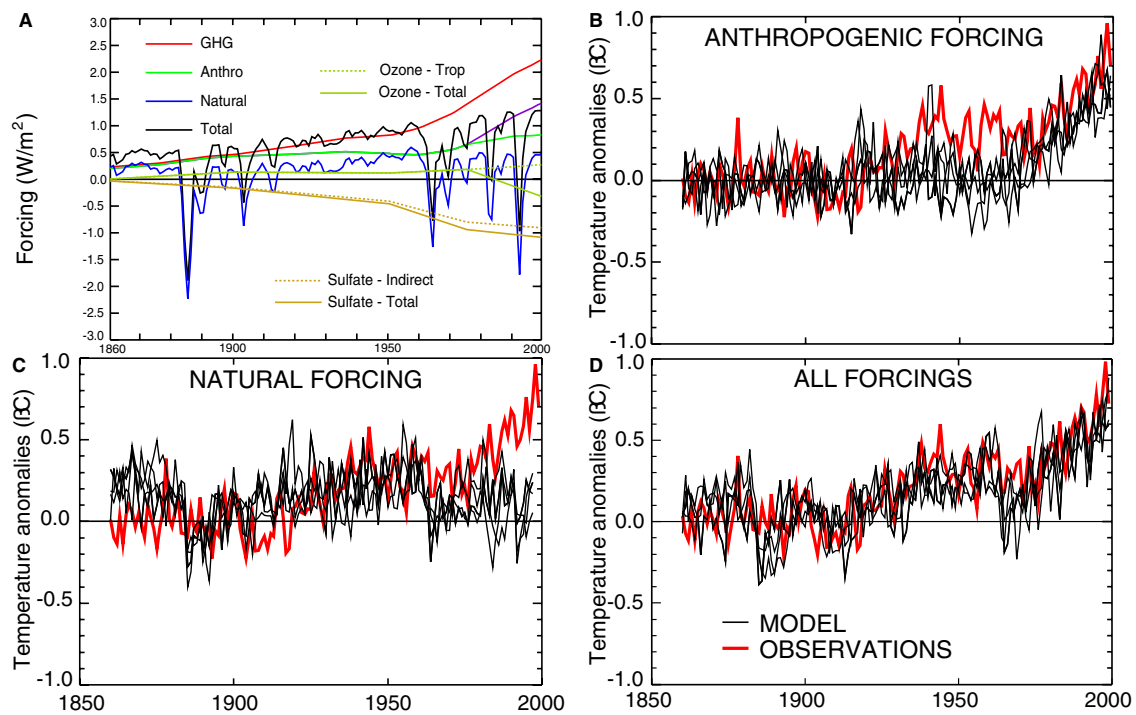


Figure 3. Global mean forcing and temperature anomaly in the UK Meteorological Office 2000 model^{29,30} for the period 1860 to 1998. Results of four model runs are shown for each indicated combination of forcings together with observed temperature anomaly (red). For model sensitivity, aerosol forcing, and investigator characterization of model performance see Table 1.

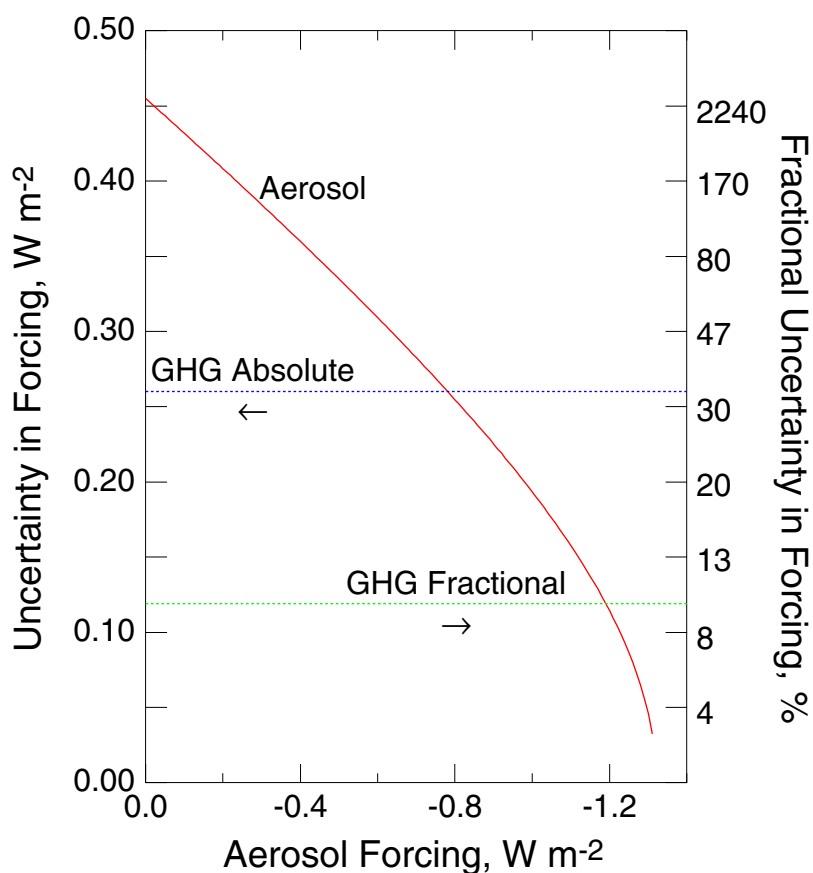


Figure 4. Absolute (left axis) and relative (right axis) uncertainty in radiative forcing of climate change by anthropogenic aerosols (red) required to achieve uncertainty of 20% in total radiative forcing over the industrial period, and in turn uncertainty of 30% in climate sensitivity as a function of (negative) aerosol forcing. Blue and green lines denote for comparison IPCC estimate⁷ of present uncertainty in greenhouse gas forcing.